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Mechanical properties and deformation behavior of cast binary Ti-Cr alloys

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1* Identify the short form here as you did in the 2nd sentence of the Introduction: "commercially pure titanium."

Abstract

As-cast Ti-Cr alloys prepared by using a dental cast machine with Cr contents ranging from 5 [space?] 4* to 30 wt% ~~have been~~ were investigated. The ~~E~~experimental results indicated that ~~the Ti-Cr~~ these alloys obviously had ~~obviously~~ different deformation behavior with various amounts of Cr ~~contents~~ [redundant]. The bending strength of the Ti-20Cr alloy was about 1.8 times greater than that for $\boxed{\text{c.p. Ti}}$. The Ti-10Cr alloy had *1 relatively higher bending strength [comma], almost as much as ~~near~~ the Ti-20Cr alloy. This property is believed to be a 2* result of the strengthening effect of the ω phase. From SEM fractographs, the Ti-10Cr alloy was ~~featured~~ characterized by coarse cleavage facets in the fractured surface together with some terrace-type morphology. The Ti-20Cr exhibited ductile properties [semi-colon] ~~but not for~~ however, [comma] alloys with other compositions did not exhibit such properties. In addition, the elastic recovery capability of the Ti-20Cr alloy was greater than that of c.p. Ti by as much as 460%. ~~From~~ In the unetched optical micrographs, the surfaces of 3* the Ti-20Cr alloys were covered with large ~~amounts~~ numbers of slip bands [comma] ~~It showed~~ thereby showing that the deformation of the Ti-20Cr alloy was dominated by a slip ~~of~~ in dislocation~~s~~. By judging from the results of the mechanical properties and deformation behavior, Ti-20Cr is considered to be the most ~~expected~~ feasible alloy for prosthetic dental applications if other properties necessary for dental casting are obtained.

Keywords: Titanium alloy; Chromium; ω phase; Mechanical properties

2* Identify the acronym "SEM": scanning electron microscopy (according to p.5).

3* Use "number(s)" with countable nouns such as "bands" and "amount(s)" with uncountable nouns such as "content."

4* Should the syntax be % wt throughout this report? The phrase "wt %" does not sound correct to me.

1. Introduction

Titanium and titanium alloys have become very two ~~one~~ of the most attractive biomaterials due to their light weight, high biocorrosion resistance, biocompatibility and mechanical properties. Commercially pure titanium (c.p. Ti) has also established a reputation for excellent biocompatibility as a dental metal [comma] being ~~and is~~ suitable for dental prosthetic applications [1,2,3]. [space after each comma] However, [comma] There are some inherent problems that must be overcome for titanium to be used successfully in dentistry. The fact that pure titanium has a high melting temperature and high reactivity with oxygen and impurities at elevated temperatures makes it difficult to cast [4]. Moreover In addition, reducing the melting temperature of titanium also can ~~could~~ decrease the risk of inadequate mold filling and porosity development due to the considerable ~~temperature~~ difference in temperature between the molten alloy and the much cooler investment [5]. On the other hand, since the properties of unalloyed titanium are not suitable for all purposes, many titanium alloys for dental use have been developed, and their properties have been studied [1,6-9], [delete comma] mainly to improve the strength and castability of pure titanium.

One method for ~~of~~ solving these problems is to use titanium alloys, which can ~~could~~ exhibit solid solution hardening and have lower fusion temperatures and better ductility than c.p. Ti [6]. Titanium can also be alloyed with a variety of elements to alter its properties, namely; [delete semi-colon] to improve strength, high [hyphen] temperature performance, creep resistance, weldability and formability [1]. For a metal to be used in ~~a~~ dental restoration, it should be biocompatible so that it does not cause harmful toxicological or allergic reactions to the patient. Among the various titanium alloys, Ti-6Al-4V [redundant] ~~alloy~~ is the most widely used because of its better physical and mechanical properties in comparison to c.p. Ti [1]. However, it ~~there~~ has been ~~a~~ speculated ~~speculation~~ that the release of Al and V ions from the alloy might cause some long-term health problems [10-12]. Moreover, the low wear resistance of Ti-6Al- 4V can ~~could~~ accelerate the release of such harmful ions [13-15]. Searching ~~The searches~~ for alternatives capable of satisfactorily replacing the

1* "Research" is uncountable. Do not attempt to make it plural! Furthermore, uncountable nouns cannot take an indefinite article.

1 * traditionally used alloys have made titanium become a ~~target~~ focus for research~~es~~ in prosthetic dentistry.

[comma before & after insert]

In the 1980s, Ti-Cr alloys were reported ~~as~~ to hav~~ing~~e high tensile strength and good ductility for dental casting alloys as well as Ni-Cr and Co-Cr ~~alloys~~ [16,17]. In our previous study [18], the hardness of a series of binary Ti-Cr alloys with Cr content~~s~~ ranging from 5 to 30 wt% [space?] ~~had been~~ was investigated. We found that the hardness of the Ti-Cr alloys became ~~higher~~ greater as the Cr content~~s~~ increased, ~~and~~ rang~~ed~~ing from 296 HV to 428 HV. The present ~~study~~ research is a continu~~al~~ed ~~research~~ study of this alloy system, ~~with the~~ focusing on the mechanical properties and the deformation behavior of these titanium alloys. Also, the mechanical properties of ~~the~~ these cast ~~Ti-Cr~~ [redundant] alloys ~~were~~ are investigated to judge ~~the possibility~~ their feasibility for ~~the~~ practical dental applications.

1 *

2. Materials and Methods

The materials used for this study include c.p. Ti, Ti-5Cr, Ti-10Cr, Ti-20Cr, Ti-25Cr and Ti-30Cr alloys (in wt%) [space?]. ~~Based on~~ On the basis of the Ti-Cr phase diagram [19], the eutectoid composition is approximately ~~at~~ 13.5 wt% [space?]. The Ti-5Cr and Ti-10Cr alloys correspond to the hypoeutectoid compositions [semi-colon] ~~and~~ whereas, [comma] the Ti-20Cr, Ti-25Cr and Ti-30Cr alloys are in the hypereutectoid composition range. All the materials ~~have been~~ were prepared from raw titanium (99.8% ~~in purity~~ pure), Cr (99.95% ~~in purity~~ pure) by using a commercial arc-melting vacuum-pressure-type casting system (Castmatic, Iwatani Corp., Japan). The ingots of approximately 20 g each were re-melted five times to improve their chemical homogeneity. Prior to casting, the ingots were re-melted again. The difference in pressure between the two chambers allowed the molten alloys to instantly drop into a graphite mold at room temperature. In this study, the experimental alloys were fabricated by using a graphite mold instead of a dental investment mold.

X-ray diffraction (XRD) for phase analysis was conducted by using a diffractometer (XRD-6000, Shimadzu, Japan) operat~~ed~~ing at 30 kV and 30 mA. ~~A~~ Ni-filtered CuKα radiation was used for this study, 2* wherein the phases were ~~Phase was~~ identified by matching each characteristic peak with the JCPDS files. 3*

2* "Radiation" is an uncountable noun. Do not precede with an indefinite article.

3* Where is your identification of the acronym "JCPDS"?

1* Is this the typical method for calculating the modulus of elasticity in bending? If so, "is" is correct. However, if this method can typically vary with the experiment, then "was" should be used.

Three-point bending tests were performed by using a desk-top mechanical tester (AG-IS, Shimadzu, Japan). The bending strengths were determined by using the equation, $\sigma = 3PL/2bh^2$ [20], where σ is the bending strength (MPa), P is the load (kg), L is the span length (mm), b is the specimen width (mm), and h is the specimen thickness (mm). The dimensions of the specimens were [delete colon]: L = 30 mm, b = 5.0 mm and h = 1.0 mm. The modulus of elasticity in bending was(?) 1* is calculated from the load increment and the corresponding deflection increment between the two points on the straight line as far apart as possible by using the equation [delete colon]: $E = L^3\Delta P / 4bh^3\Delta\delta$, where E is the modulus of elasticity in bending (Pa), ΔP is the load increment as measured from preload (N), and $\Delta\delta$ is the deflection increment at midspan as measured from preload. The average bending strength and modulus of elasticity in bending were taken from at least five 5 tests under each condition. The elastic recovery (springback) capability for each material was evaluated from the change in deflection angle when loading was removed. The details can be found in Ho et al. [21]. The fractured surface of the ~~fractured~~ specimen after the bending test was cleaned by an ultra [no space] sonic washer. The fractured surface was observed by using ~~s~~ scanning electron microscopy (SEM; JSM-6700F, Jeol, Tokyo, Japan). Moreover ~~In addition~~, microstructures of post-bending unetched specimens were examined by using an optical microscope (BH2, Olympus, Japan).

3. Results and discussion

3.1. Phase and structure

The phase and crystal line structure of the c.p. Ti and Ti-Cr alloys are ~~was~~ shown in ~~is~~ Table 1. The crystalline structure of the binary Ti-Cr alloy is sensitive to its ~~the composition~~ [delete parentheses] (chromium content) ~~of the alloy~~ [delete verbosity]. The c.p. Ti was comprised entirely of a hexagonal α phase. With 5 [space?] wt% Cr, the metastable β phase began ~~starts~~ to be retained. When the Cr content was increased to 10 [space?] wt% or greater ~~higher~~, the β phase 2* was completely retained with a bcc crystal line structure. This finding is consistent with the early

2* What is "bcc"?

obtained by [comma] who
result s of Ericsen et al. [22], ~~They~~ reported that the β phase cannot be fully retained during

? [space] [space ?]
"at"? quenching unless the Cr content exceeds about 6 at% (6.5 wt%). Apparently, more than

Just as have
10%Cr is needed to fully retain the β phase in the Ti-Cr alloys. ~~Like~~ Fe, Co and Ni, Cr ~~has~~

[comma] so has
been recognized as ~~an~~ eutectoid β-stabilizing elements, ~~This is true for~~ the present Ti-Cr system.

being [redundant]
The ω peak was found in the Ti-5Cr and Ti-10Cr alloys, especially notable in Ti-10Cr ~~alloy~~. According to Sikka et al. [23], this ω phase may be defined by a hexagonal lattice. In many investigations, the presence and volume fraction of an ω phase in alloys of titanium and zirconium can be seen from the intensity of lines on the x-ray diffraction patterns of polycrystals or of one of the ω phase reflections in photographs of single crystals [24-26]. The

although
presence of this athermal ω phase, ~~though being~~ small in quantity, had an exceedingly important effect on the mechanical properties of the alloy, as will be discussed later.

3.2. Mechanical properties

The bending strengths of c.p. Ti and Ti-Cr alloys are shown in Fig. 1. ANOVA test results showed significant overall differences among bending strengths for c.p. Ti and Ti-Cr alloys ($p < 0.05$). All the Ti-Cr alloys had significantly higher ($p < 0.05$) bending strength (1035-1484 MPa) than the c.p. Ti (844 MPa) tested. The bending strengths of the Ti-Cr alloys showed the

[space?]
highest results in the alloy having 20 wt% Cr content. The bending strength of the Ti-20Cr

The
alloy was about 1.8 times greater than for c.p. Ti. Ti-10Cr alloy had relatively higher bending

[comma] being as much as property
strength, almost ~~near~~ the Ti-20Cr alloy. This is believed to be a result of the strengthening

the the
effect of ω phase. The ω phase occurs in some titanium base alloys in which β phase can be retained in a metastable state [25].

The elastic modulus results are shown in Fig. 2. ANOVA test results showed significant overall differences among bending modulus values for c.p. Ti and Ti-Cr alloys ($p < 0.05$). For the Ti-Cr alloys, the elastic modulus values had a tendency to increase as the chromium content increased. It is worth noting that the elastic modulus of the Ti-10Cr alloy (163 GPa) was significantly ~~higher~~ greater ($p < 0.05$) than for all the other Ti-Cr alloys and the c.p. Ti. This result may be ~~concerned~~ associated with the formation of the ω phase during quenching. The early work of Graft et al. [27] indicated that the ω phase has an unusually high elastic modulus. ~~On the other hand~~ However, although the bending strength seems to slightly decrease with Cr content for higher Cr alloys, their moduli increased significantly. For example, when the Cr content was increased to 30 wt% [space?], the modulus of the alloy increased to 147 GPa. These results indicate that, at high Cr content~~s~~, the modulus is more sensitive to Cr content than to strength. ~~The~~ Similar results ~~had~~ have also been discussed ~~on the~~ concerning Ti-7.5Mo-xFe alloys [28].

The typical bending stress-deflection profiles of the series of alloys are shown in Fig. 3. ~~While~~ Although the Ti-5Cr and Ti-10Cr alloys with ω phases failed in ~~a~~ brittleness ~~way~~ (with an average deflection of only about 2.4 and 1.8, respectively), the Ti-20Cr alloy without ω phase did not fail [comma], even after being deflected by 8 mm (the pre-set maximum). This ω phase-induced embrittlement ~~has~~ was also ~~been~~ found in other Ti alloy systems as early as the 1970s, such as Ti-V [29] and Ti-Mn [30]. Recently, Lin et al. also reported the mechanical behavior of the ω phase in a Ti-7.5Mo-xFe alloy system [31]. It is interesting to note that, despite the strong hardening effect of the ω phase, the bending strength of Ti-10Cr [comma] the alloy comprising the largest amount of the ω phase [comma] ~~(Ti-10Cr)~~ was slightly lower than those containing no ω. This result is due to the premature, brittle fracture that occurred ~~for~~ in the Ti-10Cr. The embrittling/weakening effect was very sensitive to the ~~composition, or to be exact, to the~~ Cr content of the alloy. As shown in Fig. 3, when the Cr content was ~~higher~~ greater or ~~lower~~ less than 20 wt% [space?], the alloys showed brittle properties. In this series of alloys the highest bending strength was found in the alloy around 20 wt% [space?] Cr (1484 MPa). [period]

Delete verbosity

The stress-deflection curve of the Ti-25Cr alloy exhibited ~~a stress decrease abruptly~~ an abrupt decrease in stress at ~~the~~ a deflection of about 2 mm. * ~~And then,~~ Then the stress gradually decreased, which could be related to

* Avoid the phrase "and then" in formal writing. Both words are connectors. Only one word is needed. Do not overwork the word "and."

[delete verbosity]

the crack growth. ~~In addition,~~ The Ti-30Cr alloy also showed brittleness ~~property as well~~. The lowest bending strength and deflection were found for the Ti-30Cr alloy. For both the Ti-25Cr and the Ti-30Cr ~~alloys~~, the fractured ness is believed to be the result of the inclusion of the eutectoid consistuents[delete commas] TiCr$_2$ and/or Ti$_2$Cr in the microstructure. However, the XRD failed to find these constituents, probably due to the limited detection capability of the x-ray diffractometer. This finding concurs with those of Koike et al. [32].

In this study, only the Ti-20Cr exhibited ductile properties[period]. ~~but not for alloys with other compositions in this study.~~ As indicated in the results of Koike et al. [32], increasing Cr to 19% produced the best ductility in the alloys by tensile testing. The tensile test data for binary Ti-Cr alloys found earlier by Okuno et al. [6] were 764 MPa (Ti-10Cr) and 970 MPa (Ti-20Cr); the elongation values were 0.2% (Ti-10Cr) and 2.8% (Ti-20Cr). It is worth noting that the advantage in mechanical properties of the Ti-20Cr alloy is also demonstrated in their high elastic recovery capability[delete period] ~~High elastic recovery~~ (springback)[period here]. This capability of a metal is an indication of high strength and low modulus[comma], ~~and is~~ essential properties for many load-bearing implant and dental applications. The elastic recovery capability of the Ti-20Cr alloy was greater than that of c.p. Ti by as much as 460%.

[eliminate redundancy]

3.3. SEM photography

Fig. 4(a)-(d) shows SEM micrographs of the fractured surfaces of the Ti-Cr specimens after bending tests. Since Ti-20Cr alloy did not fail during a bending test, its micrograph was not examined. The Ti-10Cr alloy was ~~featured~~ characterized by coarse cleavage facets in the fractured surface, which are characteristic of decreased ductility, together with some terrace-type morphology. At a higher magnification (Fig. 5(a)), the terrace-type morphology was more obvious, being similar to that observed in a recent report ~~of~~ by Lin et al. [31]. The fractured structures of the Ti-25Cr alloy (Fig. 4(c)) exhibited mainly cleaved grains. ~~On the other hand~~ However, dimple ruptures, indicative of a typical

[delete verbosity]

ductile fracture, were observed in the fractured structures of the Ti-25Cr alloy at a higher magnification view ~~of~~ in the SEM fractographs (Fig. 5(b)). Also, the fractured surface showed some dimple ruptures with ~~some~~ coalescence of microvoids. The fractured surface morphology of the Ti-30Cr alloy (Fig. 4(d)) revealed completely cleaved grains. The cleavage fracture ~~is in agreement with~~ corresponds to the highly brittle failure of this specimen indicated by the extremely low value of the bending deflection (~~roughly about~~ approximately 1.5 mm). As shown in Fig. 4(a), the fractured surface topography of the Ti-5Cr alloy revealed cleaved grains with some coalescence of sub-micron-sized dimples, and the cleaved grains were much smaller than that of the Ti-10Cr or the Ti-30Cr alloy. The cleavage nature of the fracture seen in these fractographs is consistent with a fracture deflection of 2.4 mm exhibited by this specimen, ~~which are~~ being larger than that of the Ti-10Cr (1.8 mm) and Ti-30Cr (1.5 mm) alloys.

3.4. Optical micrographs of as-bent surfaces

Fig. 6 compare~~d~~s the as-bent convex (tensile stress) side ~~(tensile stress side)~~ surface morphologies of the Ti-Cr alloys. ~~It can be seen from~~ These unetched optical micrographs indicate that the surfaces of the Ti-5Cr, Ti-20Cr and Ti-25Cr alloys were covered with large ~~amounts~~ numbers of slip bands, especially obvious ~~for~~ in the Ti-20Cr ~~alloy~~. ~~It~~ These micrographs also show~~ed~~ that the deformation of the Ti-20Cr and Ti-25Cr alloys was dominated by slips ~~of~~ in dislocations. [In addition], Moreover the Ti-25Cr alloy showed the cracks along the grain boundaries. ~~On the other hand~~ However, the surfaces of the Ti-10Cr and Ti-30Cr alloys ~~were~~ did not ~~found~~ reveal any slip bands; [semi-colon] ~~so~~ therefore, it was evident that these two alloys ~~were~~ had little plastic deformation.

For a metal to be used as a clasp on removable prosthetics, high elongation is desirable to minimize the risk of breakage. Also, if such an alloy is accidentally stressed beyond its proportional limit, a high elongation value will insure against fracture [33]. Alloys exhibiting high elongation values coupled with high tensile strengths usually have good fracture

* In this context, "literature" is an uncountable noun. Do not attempt to make it plural.

resistance [34]. Thus, ~~we should not use~~ brittle alloys should not be used for dental applications even if their strength is sufficient. Therefore, from an engineering ~~point of view~~ perspective, not only should a Cr content of 5, 10, 25 and 30 wt % ~~should~~ be avoided, but also a uniform distribution ~~in~~ of Cr ~~is also important~~ should be employed ~~for~~ in such an alloy system. When any process-induced segregation ~~occurred~~ occurs, ω-induced embrittlement may ~~occur~~ appear in any local regions which happen to have a Cr concentration away from 20 wt %.

Our study indicated that the Ti-20Cr alloy did not exhibit ~~the feature of~~ breaking or cracking during the bending test before ~~the~~ a deflection of 8 mm, a feature which may reduce the risk of breakage or fracture of partial dentures in clinical use. * ~~According to~~ In the ~~literatures~~ literature, Oda et al. [35, 36] reported that an experimental cast of a Ti-20Cr alloy had the least tarnish when immersed in an acidic saline solution containing fluoride or hydrogen peroxide. ~~Also~~ Moreover, Takemoto et al. [37] ~~stated~~ found that the Ti-20Cr alloy had a greater resistance to corrosion in a fluoride-containing saline solution than did c.p. Ti due to the formation of a chromium-rich oxide film. Consequently, ~~by~~ when judging from the results of this study of mechanical properties and deformation behavior ~~in this study~~, the Ti-20Cr alloy is considered to be the most ~~expected~~ feasible alloy for prosthetic dental applications if other properties necessary for dental casting are ~~obtained~~ observed.

4. Conclusion~~s~~

(1) The bending strengths of all the Ti-Cr alloys (1035-1484 MPa) were significantly higher than that of c.p. Ti (844 MPa). The bending strength of the Ti-20Cr alloy was about 1.8 times greater than ~~for~~ that of c.p. Ti. The Ti-10Cr alloy had a relatively higher bending strength, ~~almost near~~ approaching that of the Ti-20Cr alloy. This is believed to be a result of the strengthening effect of the ω phase.

(2) The elastic modulus values of the Ti-Cr alloys had a tendency to increase as the chromium content increased. The elastic modulus of Ti-10Cr alloy (163 GPa) was significantly

higher than that of all the other Ti-Cr alloys and c.p. Ti. This result may be ~~concerned with~~ due to the formation of the ω phase during quenching.

(3) The Ti-20Cr exhibited ductile properties; ~~but not for~~ however, in this study, alloys with other compositions did not ~~in this study~~ exhibit such properties. The elastic recovery capability of the Ti-20Cr alloy was greater than that of c.p. Ti by as much as 460%.

(4) After a bending test, SEM ~~micrographs~~ images of the fractured surfaces ~~after bending test~~ showed that the Ti-10Cr alloy was ~~featured~~ characterized by coarse cleavage facets in the fractured surface, ~~which are~~ being characteristic of decreased ductility, together with some terrace-type morphology.

(5) ~~From~~ In the unetched optical micrographs, the surfaces of the Ti-20Cr alloys were covered with large ~~amounts~~ numbers of slip bands, thereby ~~It~~ showing that the deformation of the Ti-20Cr alloy was dominated by a slip ~~of~~ in dislocations.

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Table and figure captions

Table 1 Phase and crystal line structure of c.p. Ti and Ti-Cr alloys fabricated [redundant] ~~in this study~~.

Fig. 1. Bending strengths of c.p. Ti and Ti-Cr alloys.

Fig. 2. Bending moduli of c.p. Ti and Ti-Cr alloys.

Fig. 3. Bending stress-deflection profiles of c.p. Ti and Ti-Cr alloys.

Fig. 4. SEM fractographs of Ti-5Cr (a), Ti-10Cr (b), Ti-25Cr (c) and Ti-30Cr (d) alloys.

Fig. 5. SEM fractographs of Ti-10Cr (a), Ti-25Cr (b) alloys.

Fig. 6. Optical micrographs of as-bent surfaces of Ti-5Cr (a), Ti-10Cr (b), Ti-25Cr (c) and Ti-30Cr (d) alloys.

Table 1 Phase and crystal line structure of c.p. Ti and Ti-Cr alloys fabricated [redundant] ~~in this study~~.

Alloy	Phase	Crystal line structure
c.p. Ti	α	hexagonal
Ti-5Cr	$\alpha/\beta/\omega$	hexagonal / bcc / hexagonal
Ti-10Cr	β/ω	bcc / hexagonal
Ti-20Cr	β	bcc
Ti-25Cr	β	bcc
Ti-30Cr	β	bcc

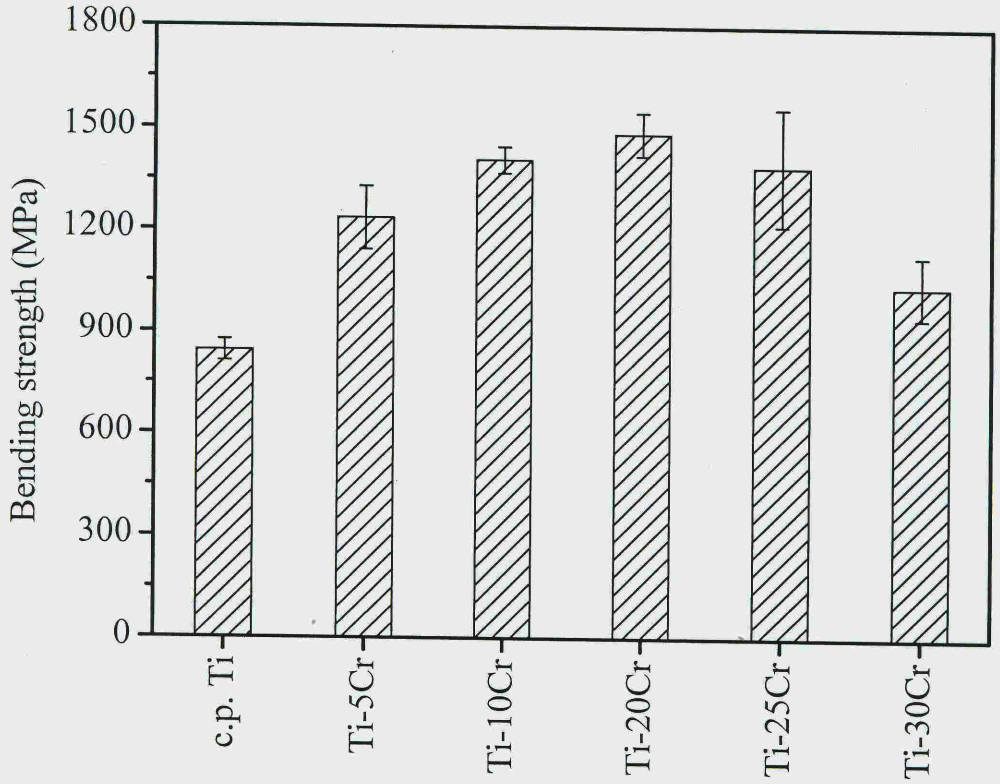

Fig. 1. Bending strengths of c.p. Ti and Ti-Cr alloys.

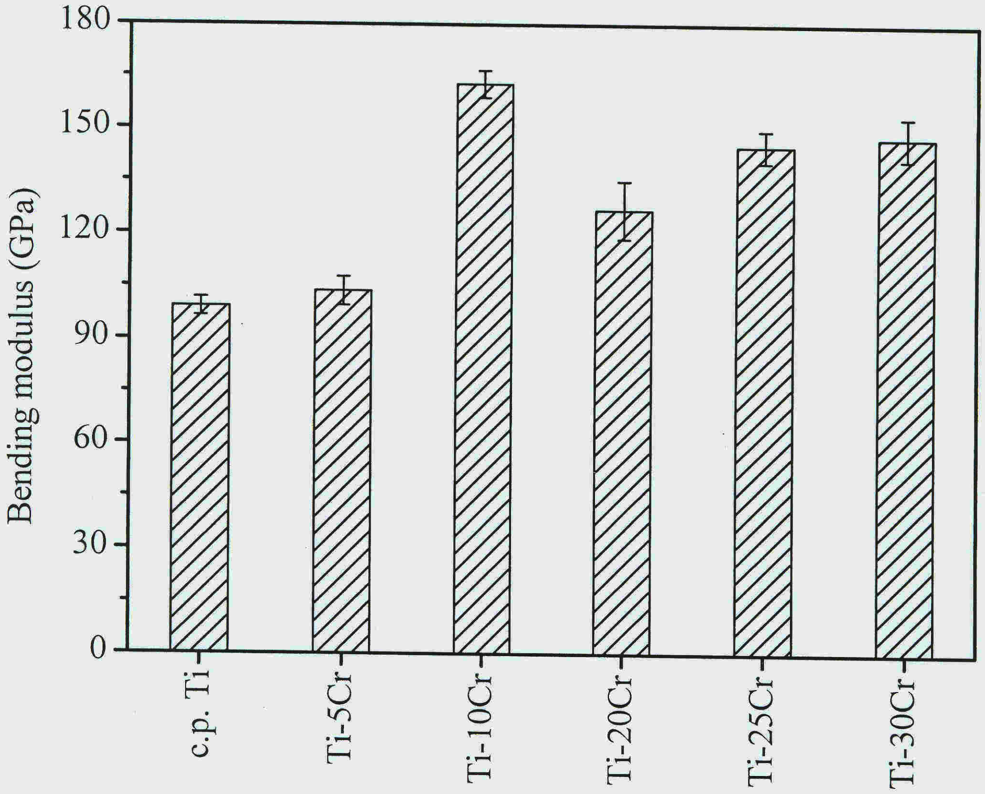

Fig. 2. Bending moduli of c.p. Ti and Ti-Cr alloys.

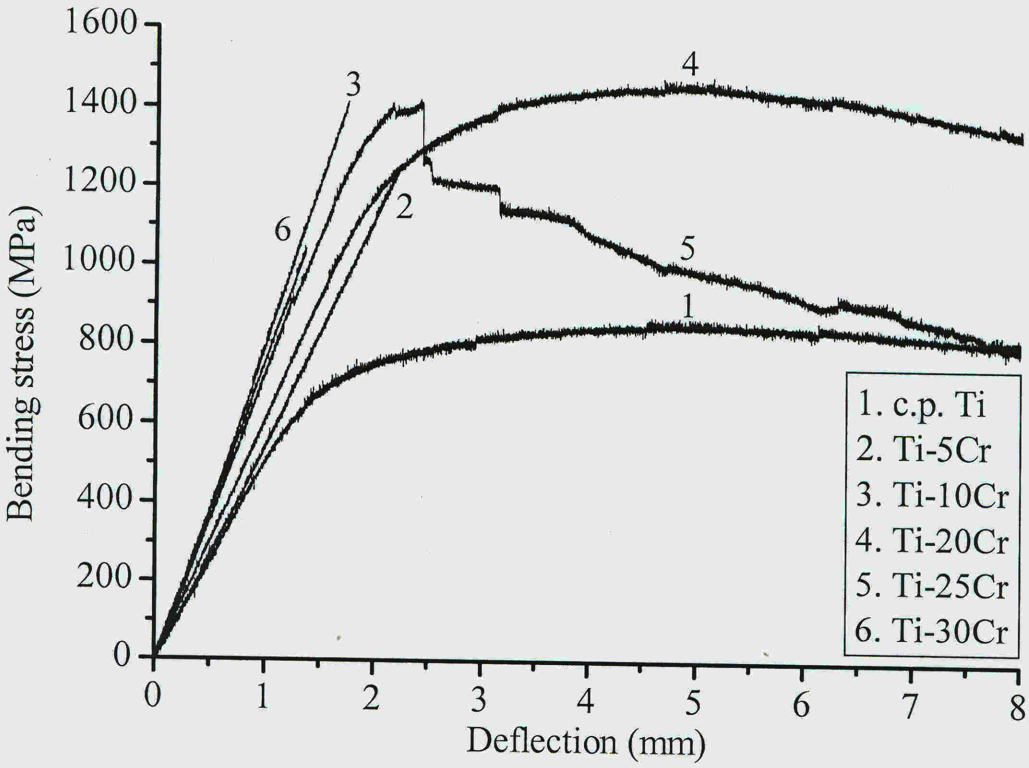

Fig. 3. Bending stress-deflection profiles of c.p. Ti and Ti-Cr alloys.

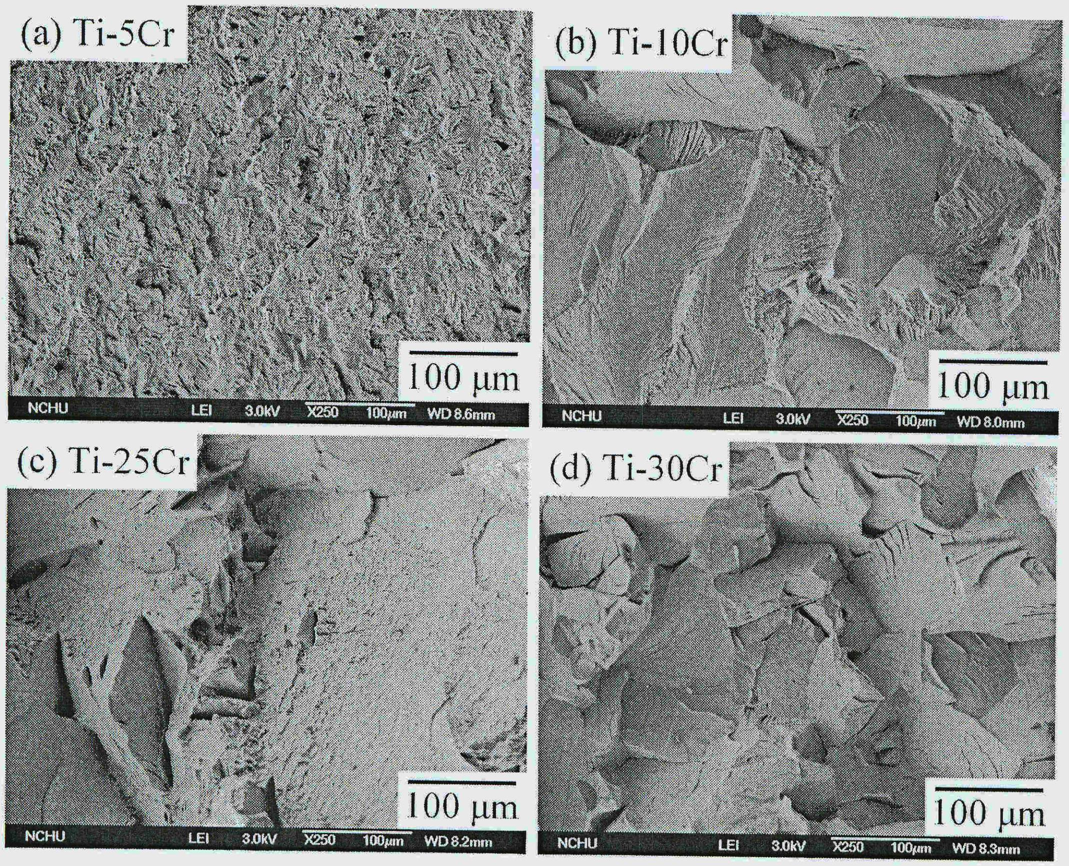

Fig. 4. SEM fractographs of Ti-5Cr (a), Ti-10Cr (b), Ti-25Cr (c) and Ti-30Cr (d) alloys.

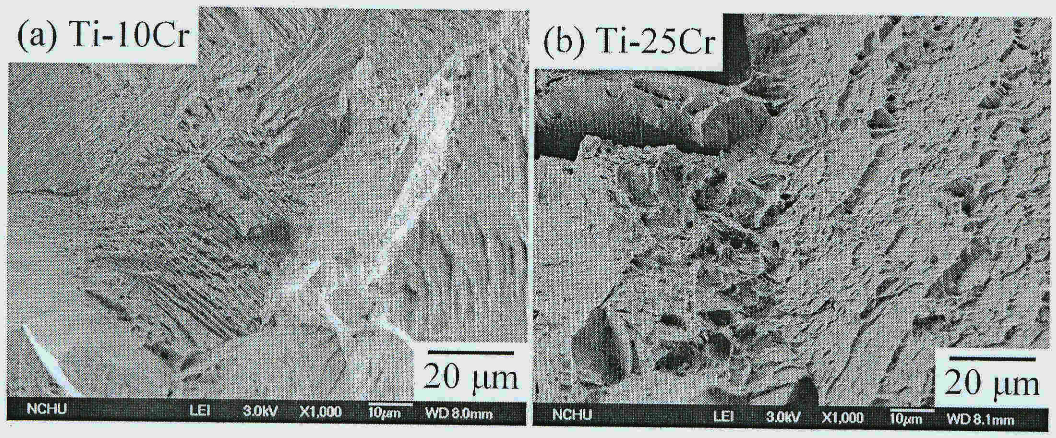

Fig. 5. SEM fractographs of Ti-10Cr (a), Ti-25Cr (b) alloys.

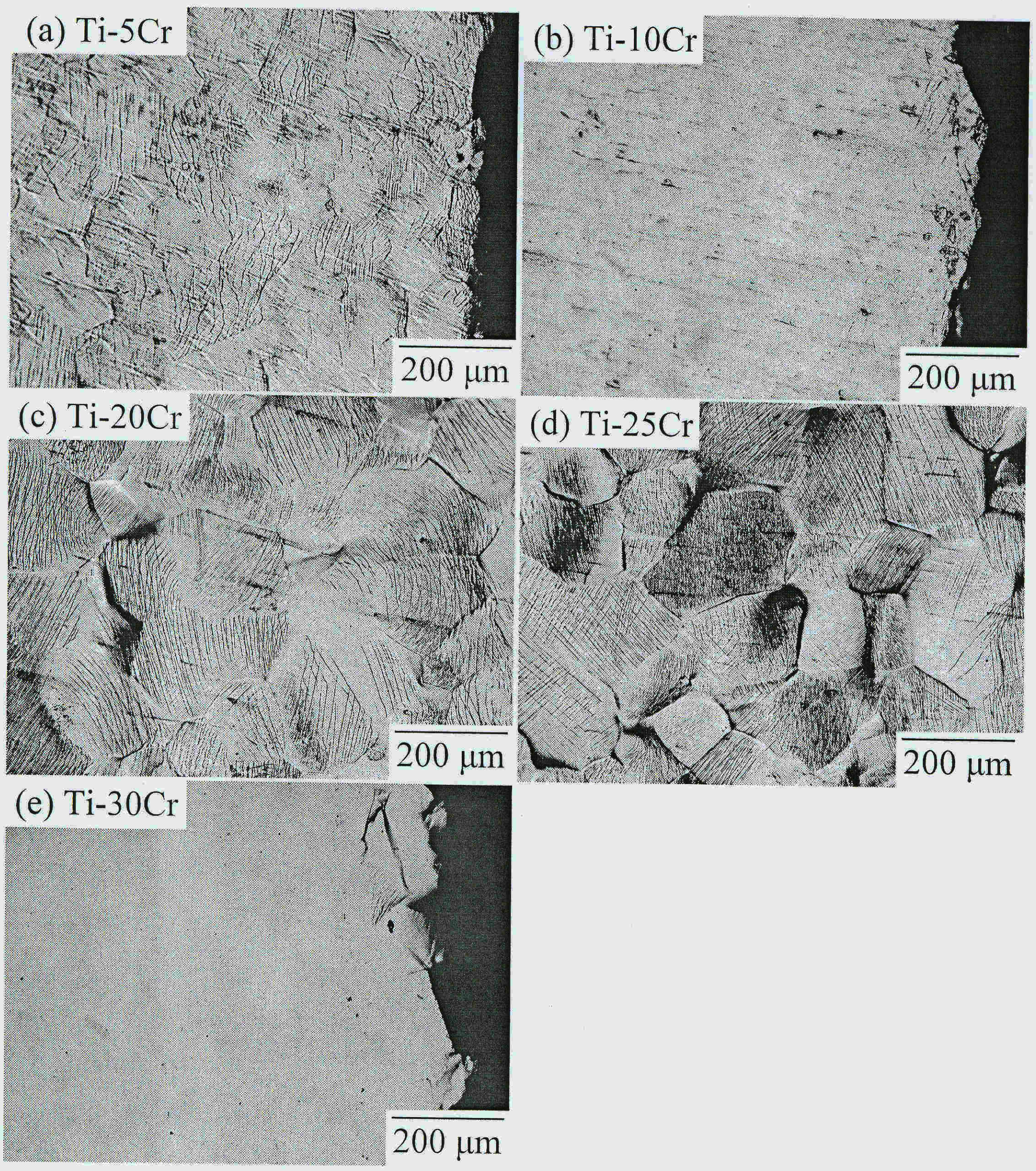

Fig. 6. Optical micrographs of as-bent surfaces of Ti-5Cr (a), Ti-10Cr (b), Ti-20Cr (c), Ti-25Cr (d) and Ti-30Cr (e) alloys.